US011990267B2

(12) United States Patent
Shi et al.

(10) Patent No.: US 11,990,267 B2
(45) Date of Patent: May 21, 2024

(54) THREE-PHASE MAGNETICS ASSEMBLY

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 635 days.

(21) Appl. No.: **17/029,294**

(22) Filed: **Sep. 23, 2020**

(65) **Prior Publication Data**

US 2022/0093325 A1 Mar. 24, 2022

(51) **Int. Cl.**

H01F 27/30 (2006.01)
H01F 3/14 (2006.01)

(Continued)

(52) **U.S. Cl.**

CPC ***H01F 27/306*** (2013.01); ***H01F 3/14*** (2013.01); ***H01F 27/263*** (2013.01); ***H01F 27/29*** (2013.01);

(Continued)

(58) **Field of Classification Search**

CPC H01F 27/306; H01F 3/14; H01F 27/263; H01F 27/29; H01F 30/12; H01F 27/38;

(Continued)

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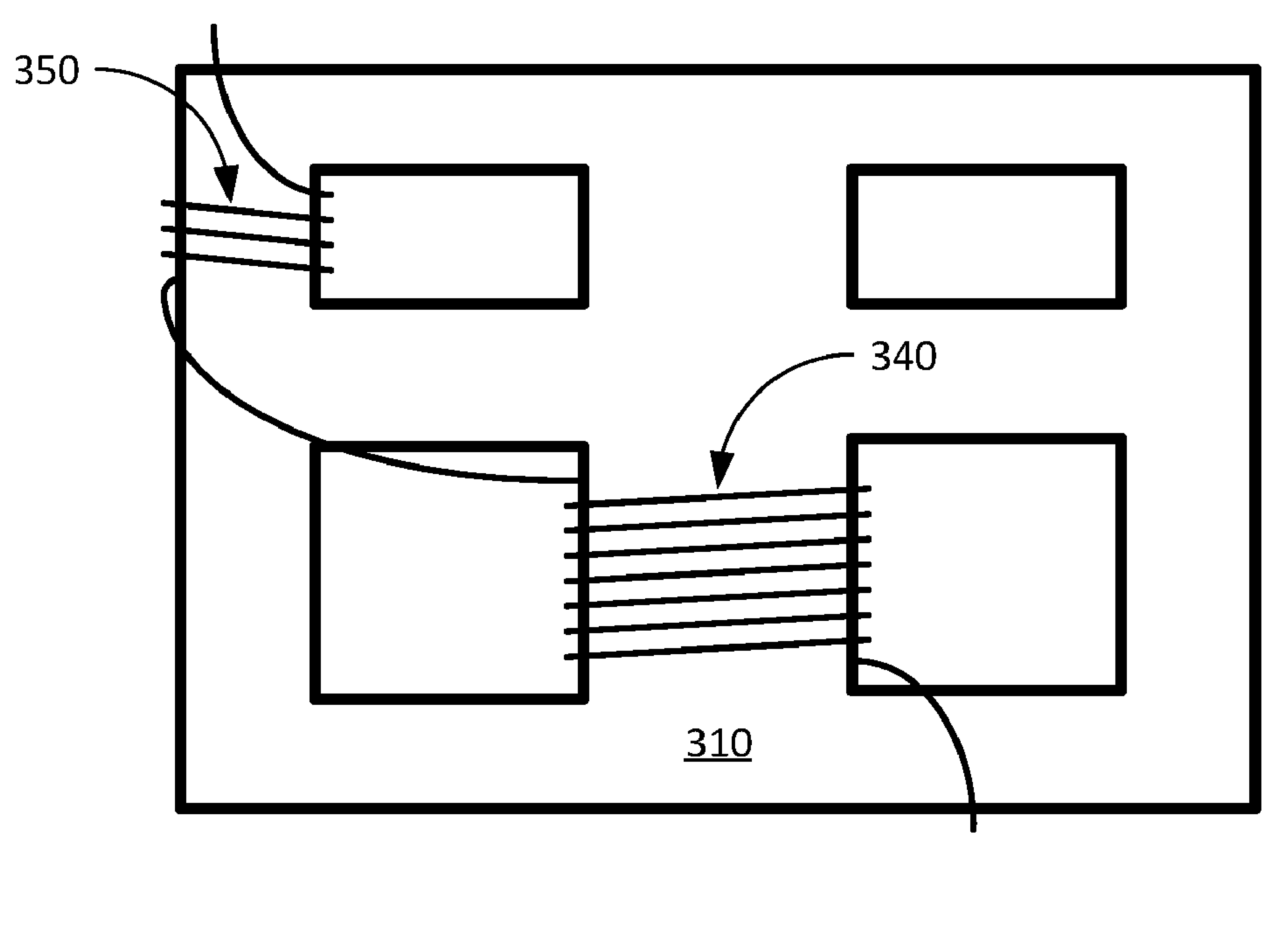
Primary Examiner — Bickey Dhakal
Assistant Examiner — Matthew T Sarles

(57) **ABSTRACT**

A three-phase magnetics assembly comprising a plurality of windings, and a unified core body is provided. The core body includes core legs which extend along central axes of the plurality of windings and around which the plurality of windings are wound such that magnetic fluxes are produced in the plurality of core legs when current flows through the plurality of windings. The plurality of windings comprise first, second, and third phase inductors, and first, second, and third phase transformers, which are positioned about the unified core body such that the core legs of the first phase inductor and second phase transformer share a central axis, the core legs of the second phase inductor and third phase transformer share a central axis, and the core legs of the third phase inductor and first phase transformer share a central axis.

17 Claims, 8 Drawing Sheets



(51) **Int. Cl.**
H01F 27/26 (2006.01)
H01F 27/29 (2006.01)
H01F 30/12 (2006.01)
H02M 3/335 (2006.01)

(52) **U.S. Cl.**
CPC ***H01F 30/12*** (2013.01); ***H02M 3/33592*** (2013.01)

(58) **Field of Classification Search**
CPC H01F 27/40; H01F 27/34; H02M 3/33592; H02M 3/003; H02M 3/01; H02M 3/33573; H02M 3/33576
See application file for complete search history.

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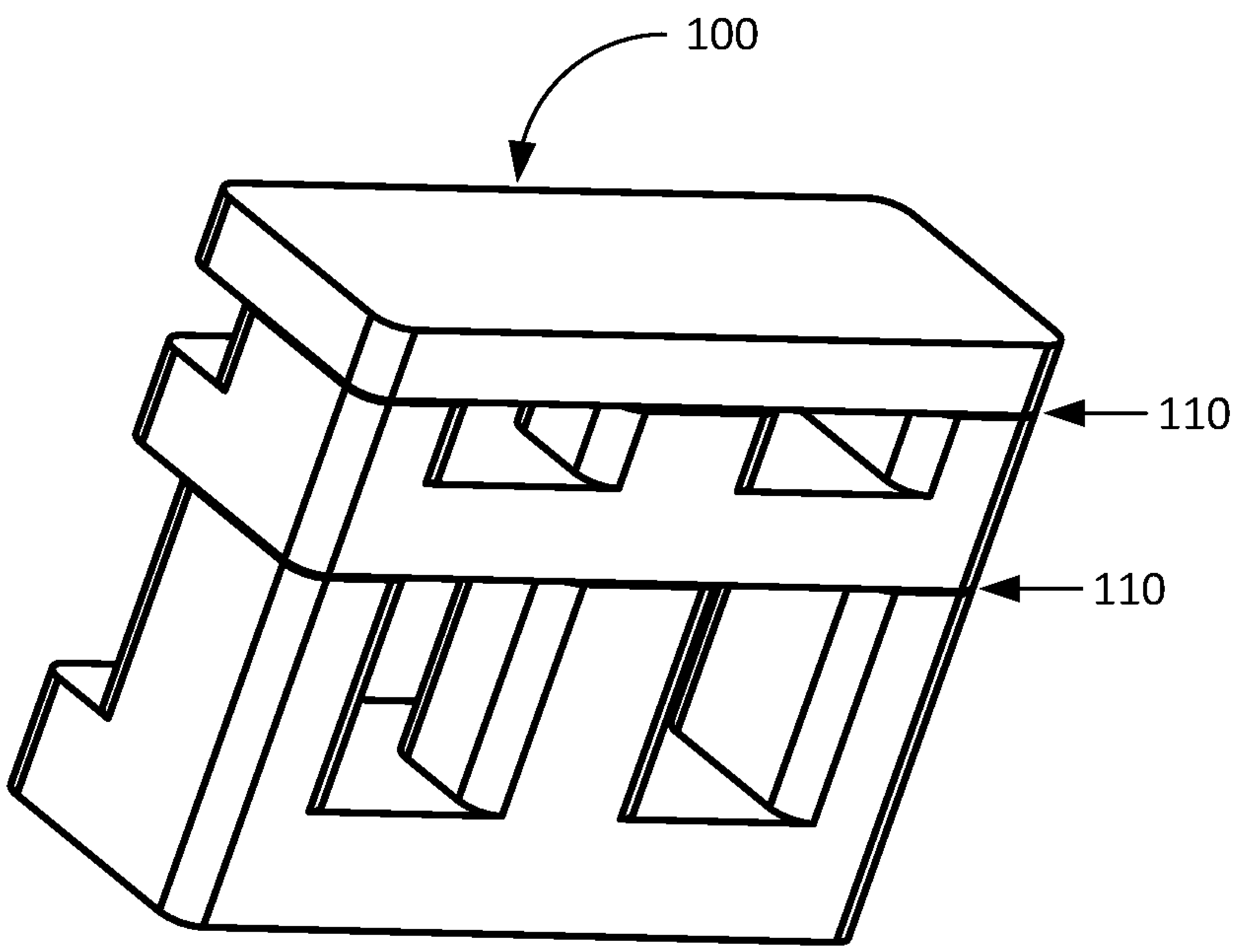

FIGURE 1A

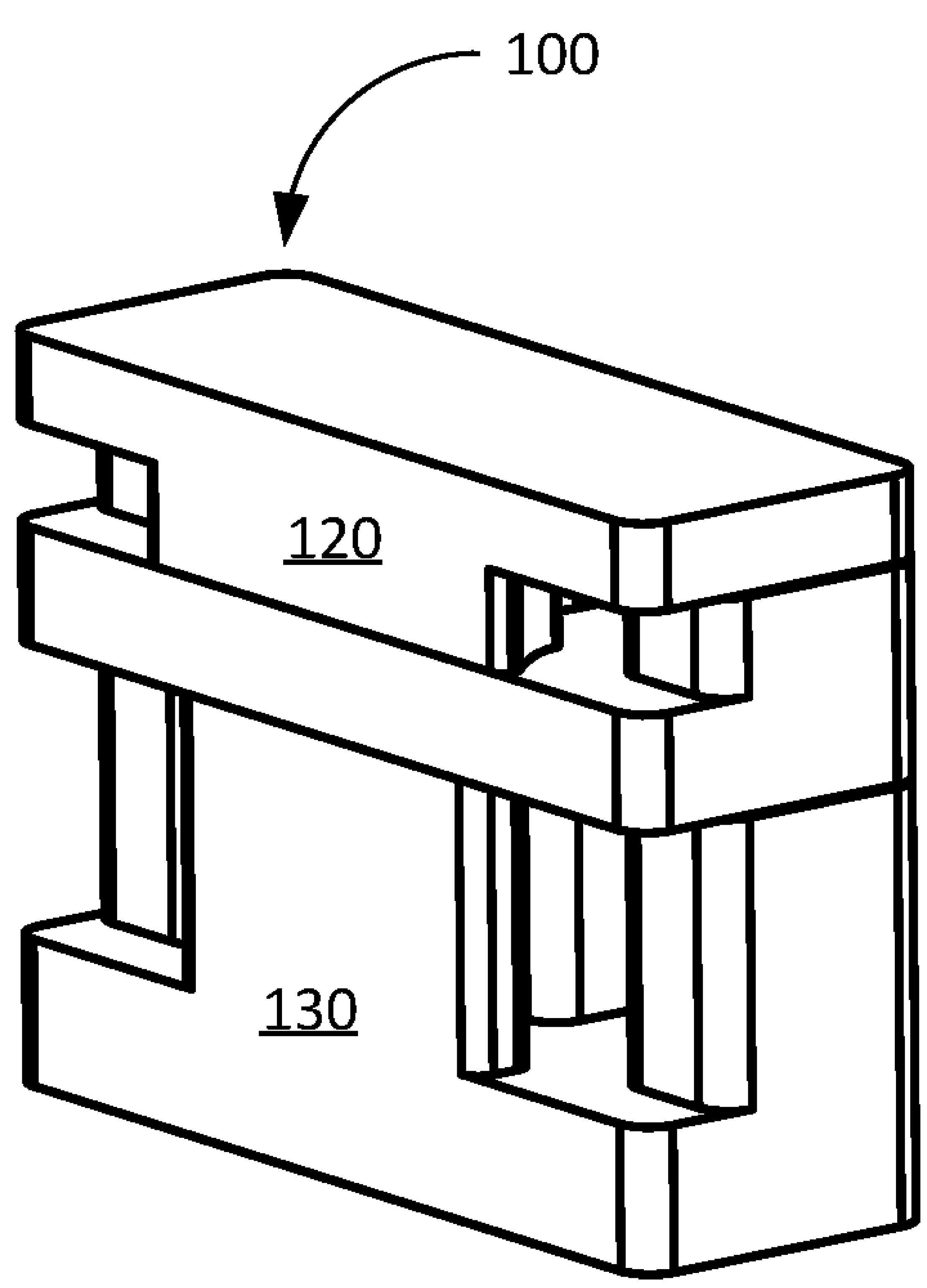

FIGURE 1B

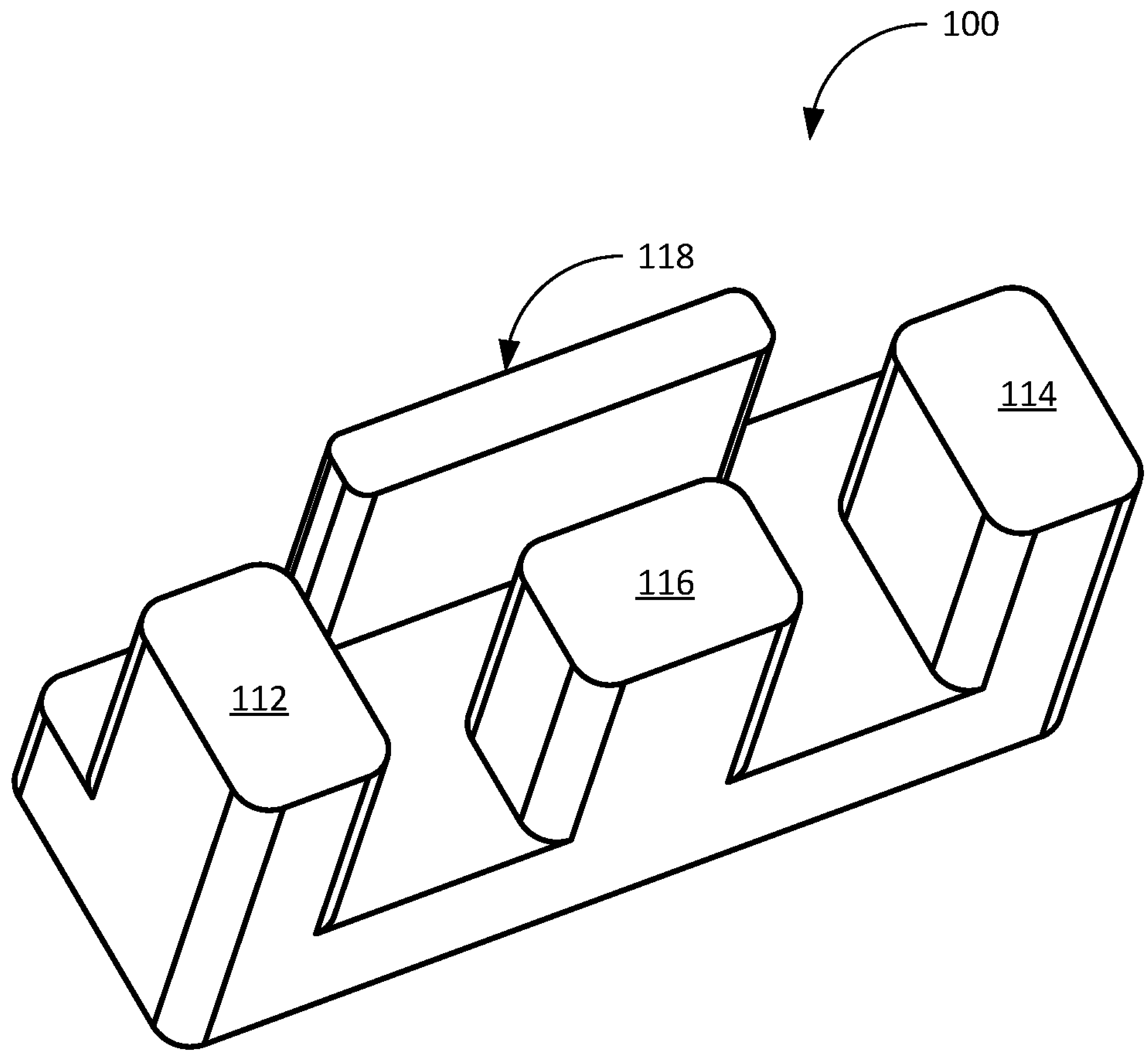

FIGURE 1C

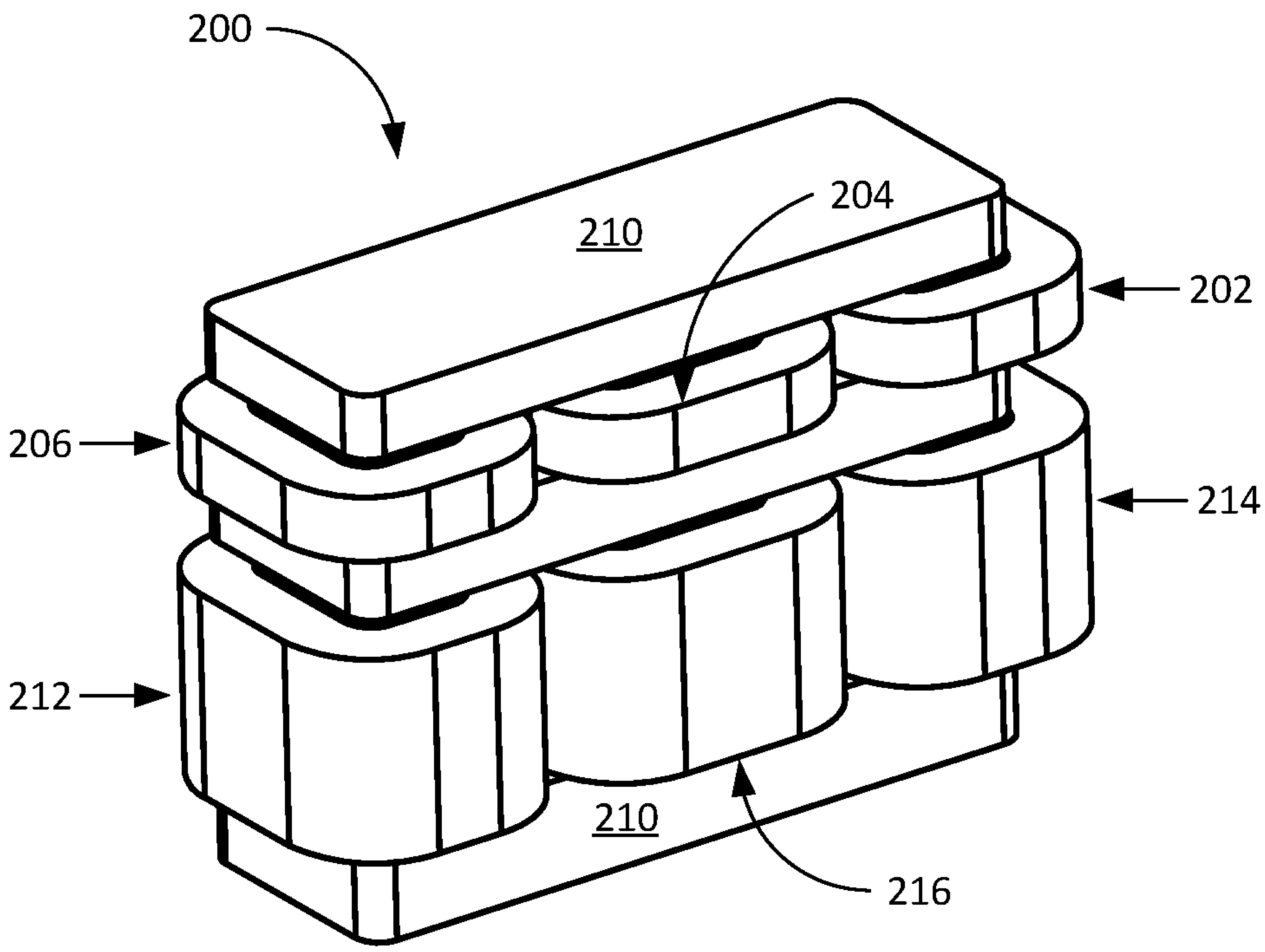

FIGURE 2A

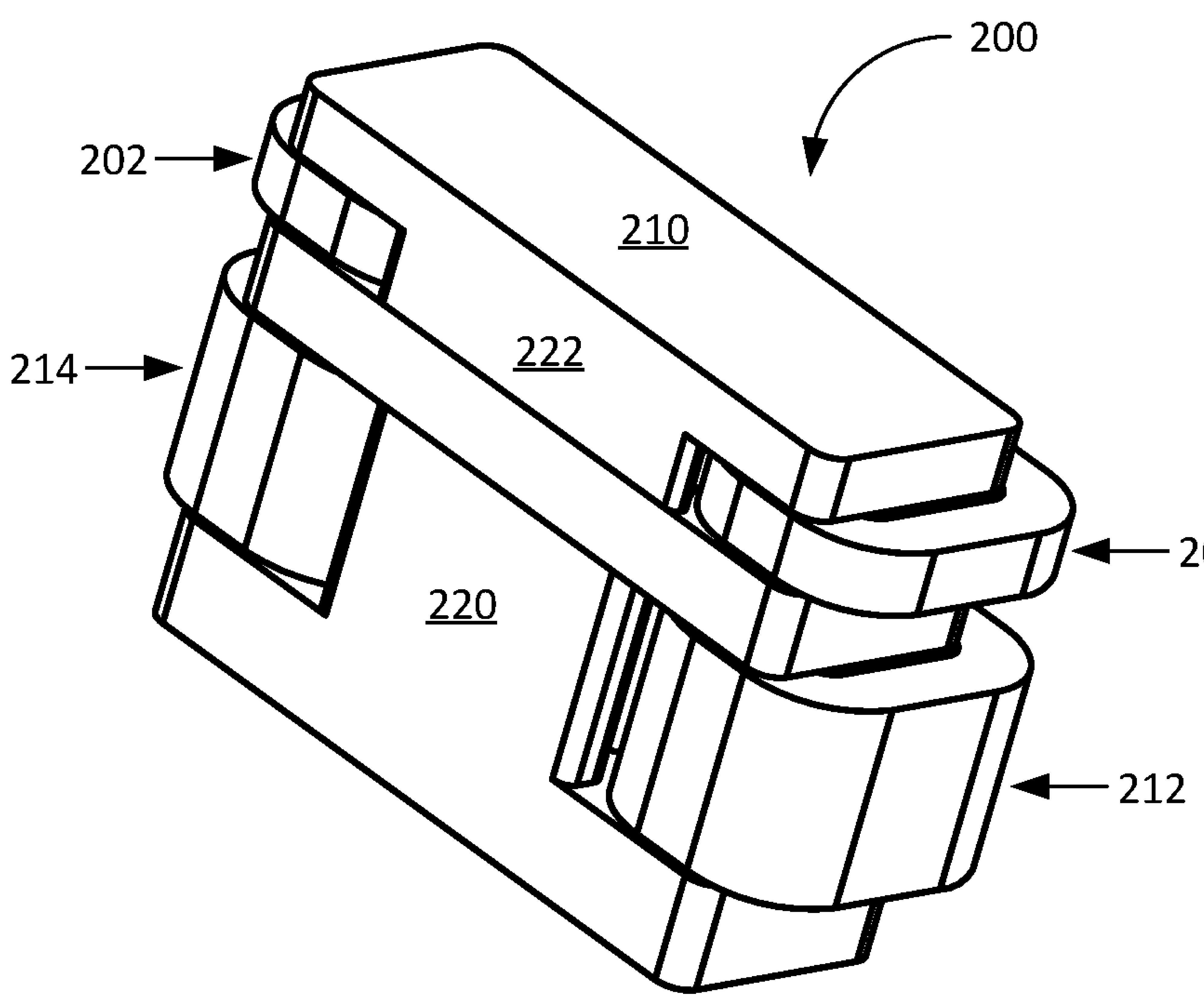

FIGURE 2B

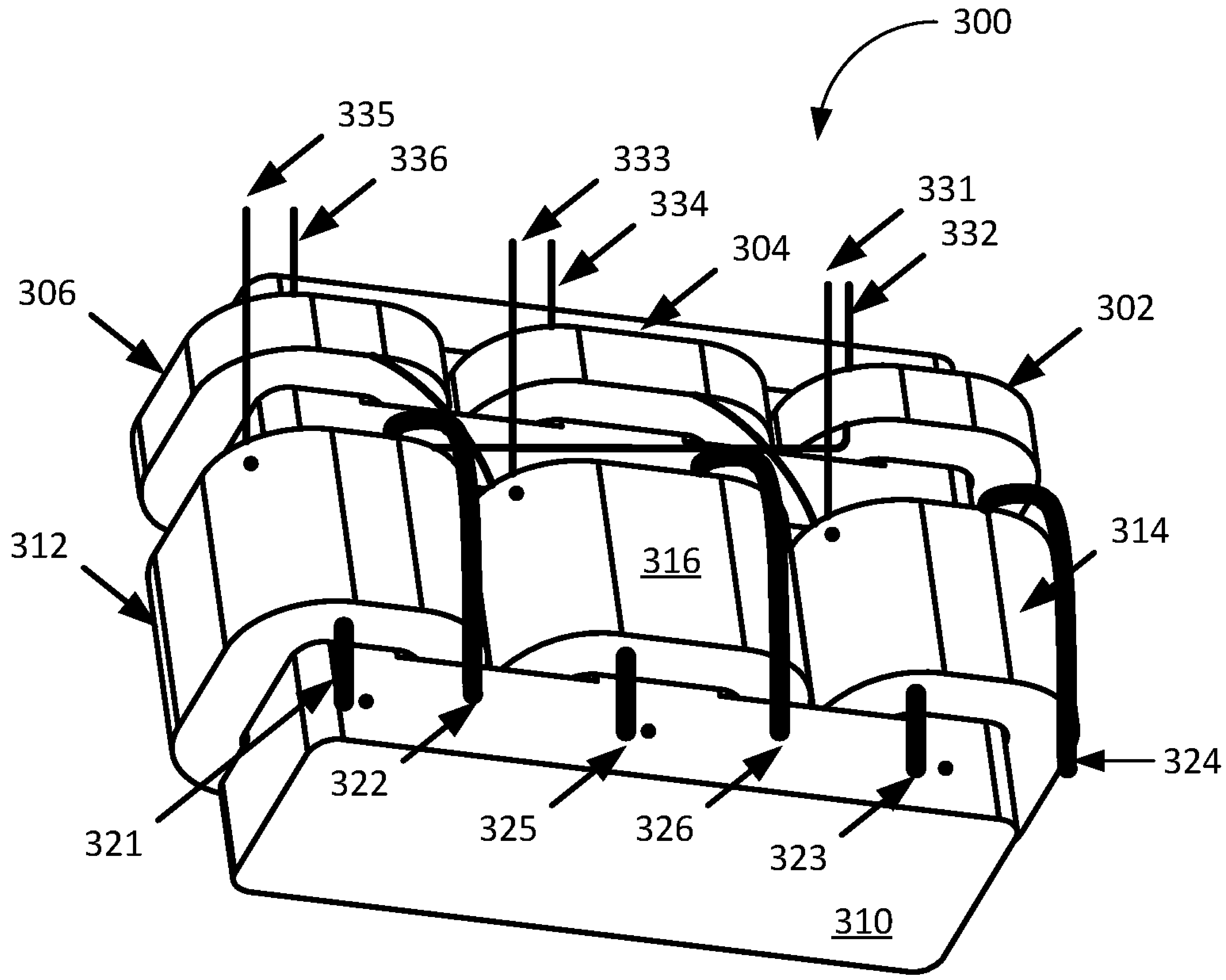

FIGURE 3A

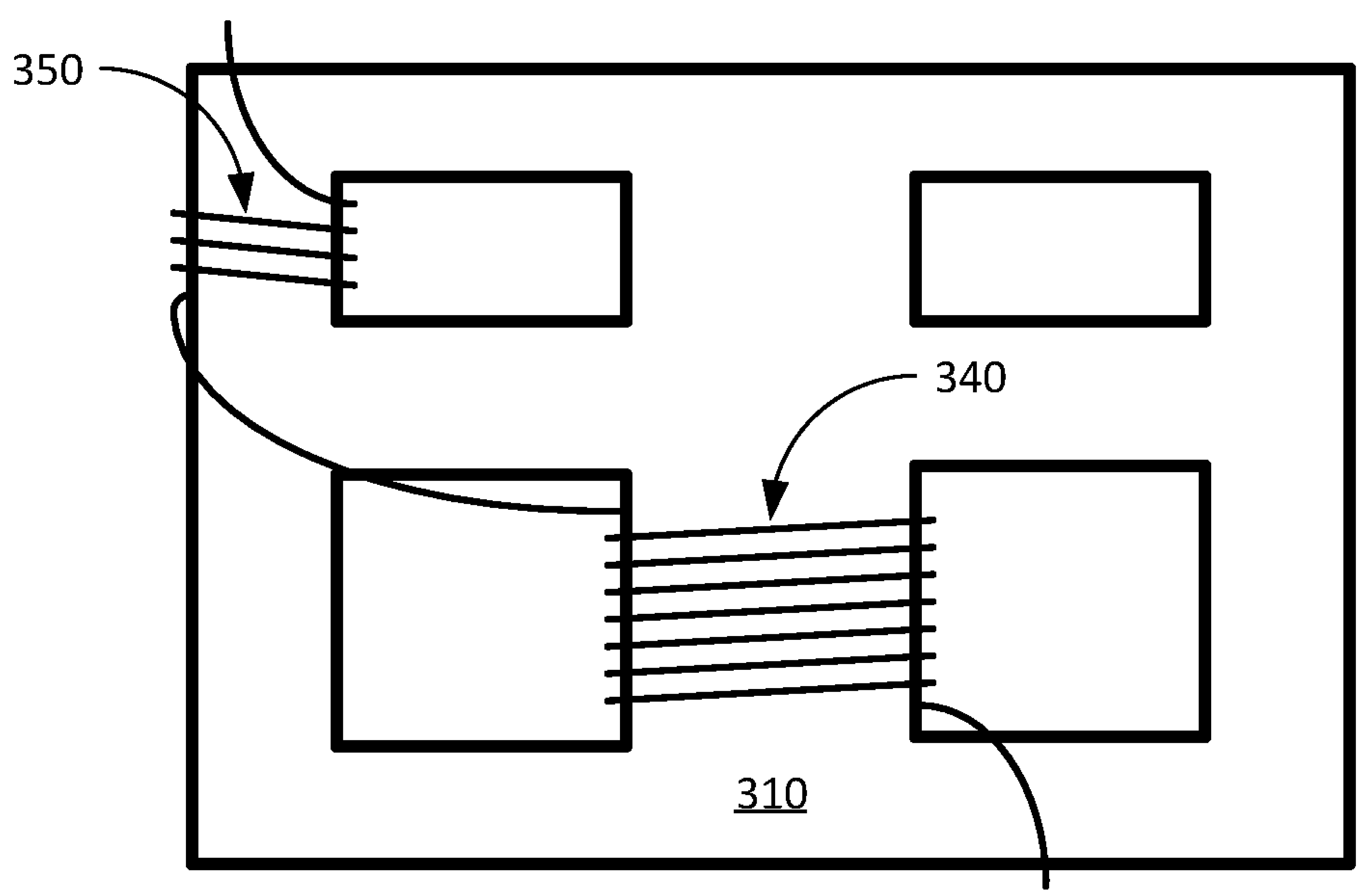

FIGURE 3B

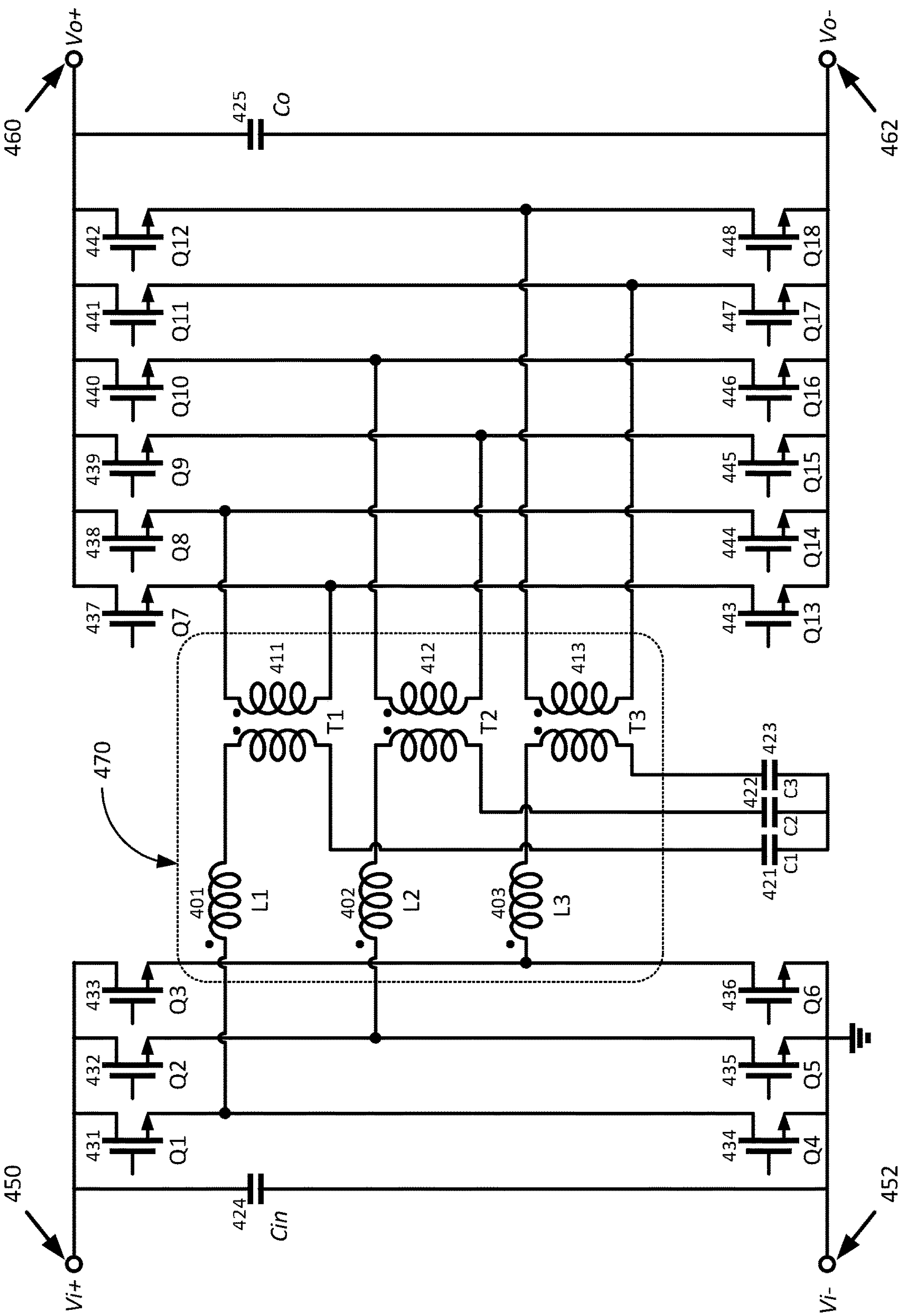
Vo+
460
425
Co
Vo-
462
442
Q12
441
Q11
440
Q10
439
Q9
438
Q8
437
Q7
448
Q18
447
Q17
446
Q16
445
Q15
444
Q14
443
Q13
411
412
413
T1
T2
T3
470
423
422
C3
C2
421
C1
401
L1
402
L2
403
L3
433
Q3
432
Q2
431
Q1
436
Q6
435
Q5
434
Q4
450
424
Cin
452
Vi+
Vi-

FIGURE 4

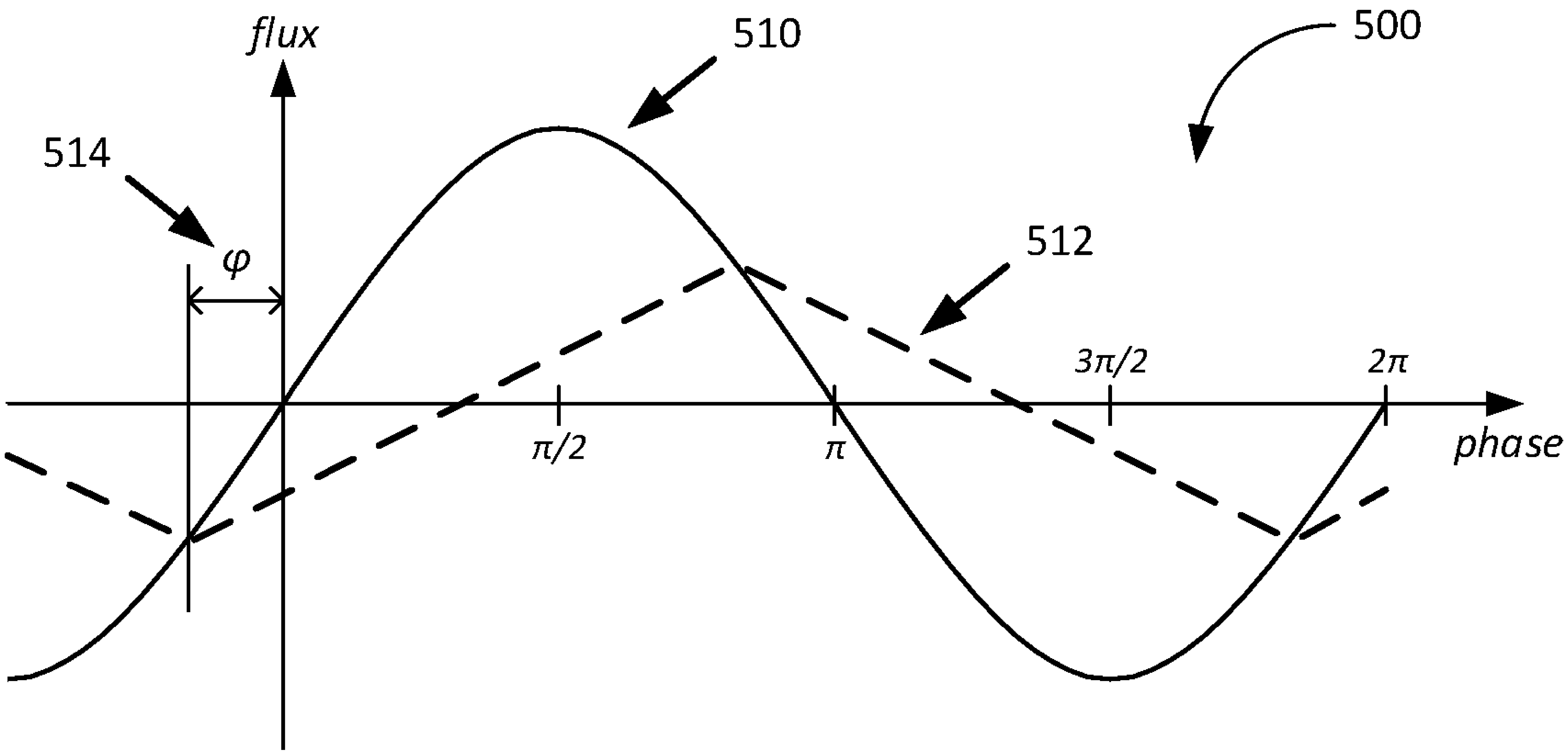

FIGURE 5A

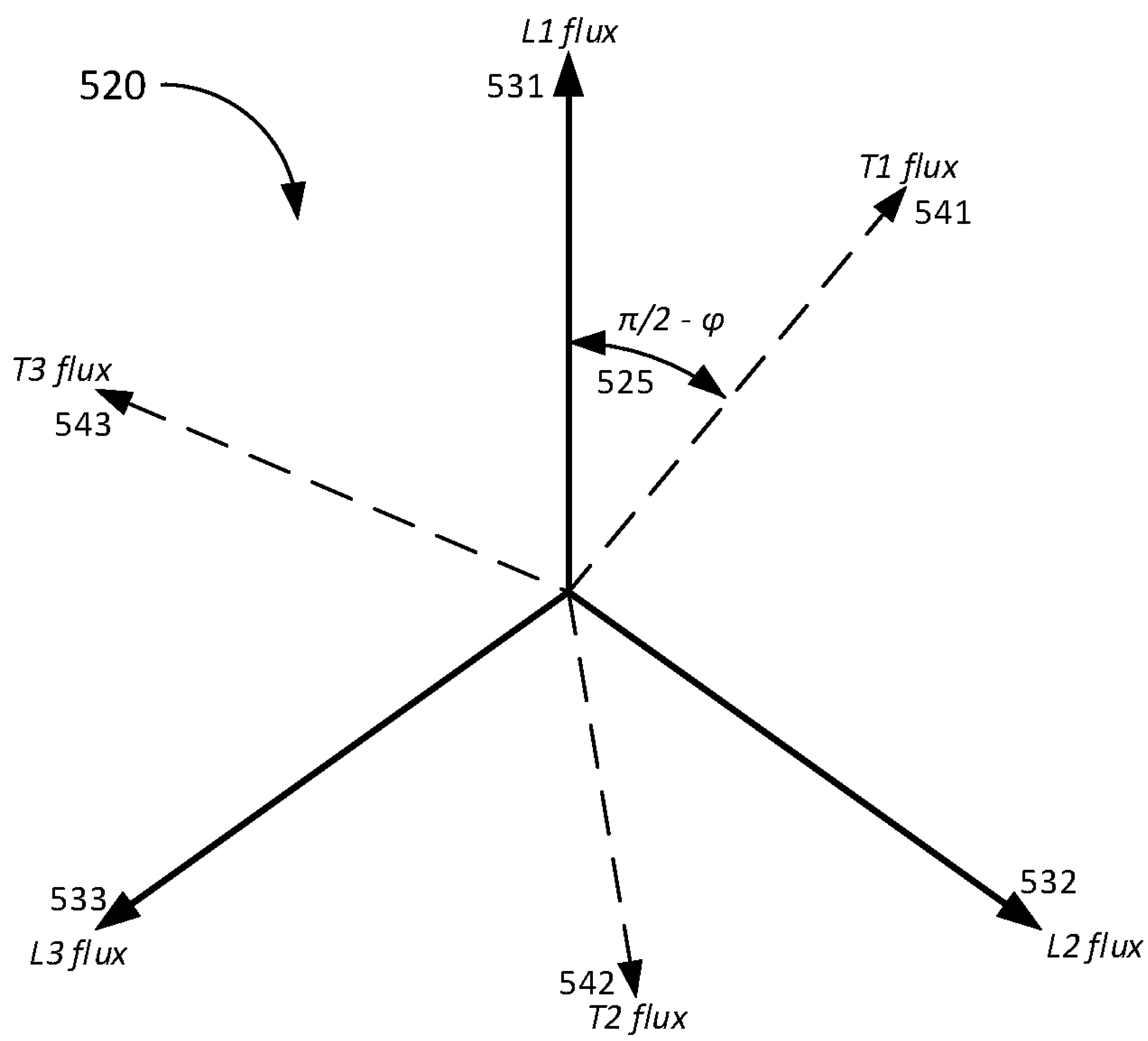

FIGURE 5B

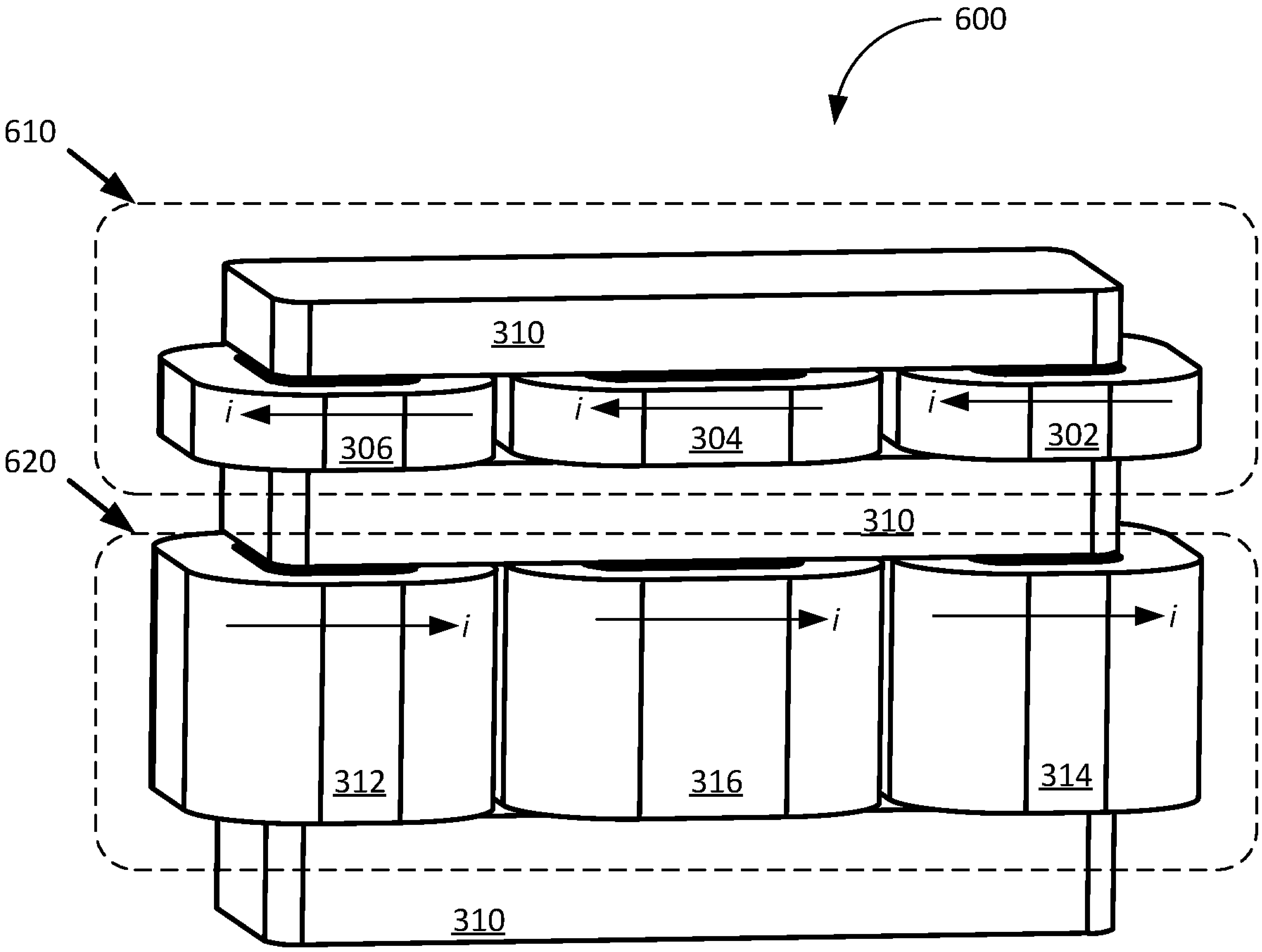

FIGURE 6

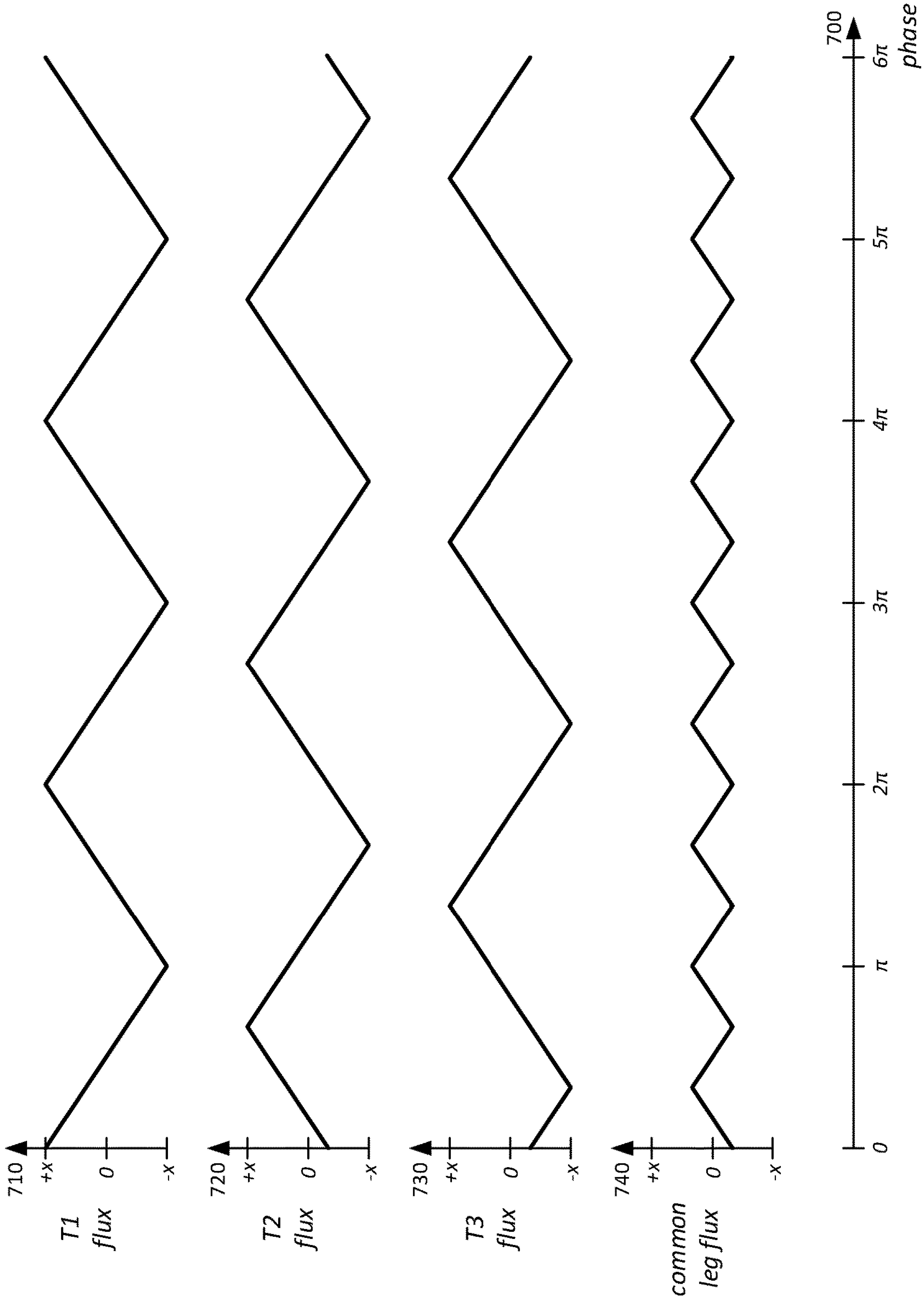
710
T1
flux
+x
0
-x
720
T2
flux
+x
0
-x
730
T3
flux
+x
0
-x
740
common
leg flux
+x
0
-x
0
π
2π
3π
4π
5π
6π
700
phase

FIGURE 7

THREE-PHASE MAGNETICS ASSEMBLY

TECHNICAL FIELD

Aspects of the disclosure are related to electronic components and in particular to inductor and transformer components for three-phase power systems.

TECHNICAL BACKGROUND

Three-phase LLC power converters are commonly used in a variety of systems including telecom systems, fast chargers for electric vehicles, and other applications requiring high power density and high efficiency.

These three-phase LLC power converters typically include an inductor/transformer pair for each of the three phases. Since these components must withstand large currents, they are commonly among the largest components within the power converter, and also dissipate energy due to core losses within these components.

OVERVIEW

In an embodiment, a three-phase magnetics assembly is provided. The three-phase magnetics assembly includes a plurality of windings, and a unified core body having a plurality of core legs which each extend in a direction of central axes of the plurality of windings and around which the plurality of windings are wound such that magnetic fluxes are produced in the plurality of core legs when current flows through the plurality of windings.

The plurality of windings comprise first, second, and third phase inductors, and first, second, and third phase transformers, which are positioned about the unified core body such that the core legs of the first phase inductor and second phase transformer share a central axis, the core legs of the second phase inductor and third phase transformer share a central axis, and the core legs of the third phase inductor and first phase transformer share a central axis.

In another embodiment, a unified core body for a three-phase magnetics assembly is provided. The unified core body includes a plurality of core legs which each extend in a direction of central axes of first, second, and third phase inductors, and first, second, and third phase transformers, each having a first and second end, and each configured to provide a magnetic core conducting magnetic flux for one of the first, second, and third phase inductors, and the first, second, and third phase transformers.

The unified core body also includes an inductor return leg, configured to conduct magnetic flux between the first and second ends of the core legs within the inductors, and a transformer return leg, configured to conduct magnetic flux between the first and second ends of the core legs within the transformers.

In a further embodiment, a three-phase magnetics assembly is provided. The three-phase magnetics assembly includes a plurality of windings, a unified core body, an inductor return leg, and a transformer return leg.

The unified core body has a plurality of core legs, each having a first and second end, which each extend in a direction of central axes of the plurality of windings and around which the plurality of windings are wound such that magnetic fluxes are produced in the plurality of core legs when current flows through the plurality of windings, wherein the plurality of windings comprise first, second, and third phase inductors, and first, second, and third phase transformers, which are positioned about the unified core body such that the core legs of the first phase inductor and second phase transformer share a central axis, the core legs of the second phase inductor and third phase transformer share a central axis, and the core legs of the third phase inductor and first phase transformer share a central axis.

The inductor return leg is configured to conduct magnetic flux between the first and second ends of the core legs within the inductors, and the transformer return leg is configured to conduct magnetic flux between the first and second ends of the core legs within the transformers.

BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the disclosure can be better understood with reference to the following drawings. While several implementations are described in connection with these drawings, the disclosure is not limited to the implementations disclosed herein. On the contrary, the intent is to cover all alternatives, modifications, and equivalents.

FIGS. **1**A, **1**B, and **1**C illustrate a unified core body for a three-phase magnetics assembly.

FIGS. **2**A and **2**B illustrate a three-phase magnetics assembly.

FIG. **3**A illustrates a three-phase magnetics assembly.

FIG. **3**B illustrates an exemplary winding within a three-phase magnetics assembly.

FIG. **4** illustrates an exemplary power converter circuit incorporating a three-phase magnetics assembly.

FIG. **5**A illustrates the relationship between inductor flux and transformer flux within an exemplary power supply circuit incorporating a three-phase magnetics assembly.

FIG. **5**B is a phase diagram illustrating the phase relationship between magnetic fluxes within each of the inductors and transformers within an exemplary power supply circuit incorporating a three-phase magnetics assembly.

FIG. **6** illustrates a three-phase magnetics assembly.

FIG. **7** illustrates magnetic fluxes within each of the transformers and a common return leg within an exemplary power supply circuit incorporating a three-phase magnetics assembly.

DETAILED DESCRIPTION

The example embodiments described herein illustrate different methods for constructing a three-phase magnetics assembly including a unified core body for use in a three-phase power system.

FIGS. **1**A, **1**B, and **1**C illustrate a unified core body **100** for a three-phase magnetics assembly. In these example embodiments, a unified core body **100** is configured to support three inductors and three transformers which are formed by a plurality of windings. Unified core body **100** includes air gaps **110** which influence various parameters of the inductors and transformers supported by the core body **100**. Unified core body **100** also includes inductor return leg **120** and transformer return leg **130**.

Inductor return leg **120** provides a return path for magnetic flux from the three inductors. Transformer return leg **130** provides a return path for magnetic flux from the three transformers.

In an example embodiment, unified core body **100** has a plurality of core legs (here three are illustrated). Each core leg has a first and second end, which each extend in a direction of central axes of the plurality of windings and around which the plurality of windings are wound such that magnetic fluxes are produced in the plurality of core legs when current flows through the plurality of windings.

FIG. **1**C illustrates a lower portion of the unified core body **100** from FIGS. **1**A and **1**B. In this example embodiment, legs **112**, **114**, and **116** provide support for, and act as magnetic cores for three transformers which consist of winding around each of legs **112**, **114**, and **116**. A portion of transformer return leg **118** is also illustrated. A similar module is used to provide support for, and act as magnetic cores for the three inductors, and would be positioned above this module during manufacture.

FIGS. **2**A and **2**B illustrate a three-phase magnetics assembly **200**. In this example embodiment unified core body **210** has been populated with three transformers **212**, **214**, and **216**, along with three inductors **202**, **204**, and **206**. FIG. **2**B also illustrates inductor return leg **222** and transformer return leg **220**.

FIG. **3**A illustrates a three-phase magnetics assembly **300**. In this example embodiment unified core body **310** has been populated with three transformers **312**, **314**, and **316**, along with three inductors **302**, **304**, and **306**. Here, primary winding outlets **331**-**336** are illustrated as wires rising to the top of magnetics assembly **300**, and secondary winding outlets **321**-**326** are illustrated as conductors flowing to the bottom of magnetics assembly **300**.

In this example embodiment, primary winding outlets **331**, **333**, and **335** are dot points indicating polarity of the primary windings, and secondary winding outlets **321**, **323**, and **325** are dot points indicating polarity of the secondary windings.

FIG. **3**B illustrates an exemplary winding within a three-phase magnetics assembly. In this example embodiment, a single winding is used to construct an inductor **350** and an inner/primary core of a corresponding (same phase) transformer **340** around unified core body **310**. Notice that the inductor **350** and transformer **340** are offset from each other on different core legs. This is done to reduce magnetic flux within unified core body **310** and is discussed in detail below with respect to FIGS. **4** and **5**.

FIG. **4** illustrates an exemplary power converter circuit incorporating a three-phase magnetics assembly **470**. This example embodiment illustrates a portion of a three-phase half-bridge LLC circuit incorporating a three-phase magnetics assembly **470**. This is simply one example use of the present invention, as three-phase magnetics assembly **470** may also be used in many other circuits such as full-bridge configurations, other half-bridge configurations, and the like.

This example portion of a power converter circuit includes inputs Vi+ **450** and Vi-**452**, input capacitor Cin **424** along with input stage N-FETs **431**-**436**. The power converter also includes three-phase magnetics assembly **470** which incorporated inductors L**1** **401**, L**2** **402**, and L**3** **403**, along with transformers T**1** **411**, T**2** **412**, and T**3** **413**. The output stage includes N-FETs **437**-**448**, output capacitor Co **425** and outputs Vo+ **460** and Vo− **462**. The example power converter circuit also includes capacitors C**1** **421**, C**2** **422**, and C**3** **423**. While this example circuit uses N-FETs, other example circuits may use P-FETs, or wide-band-gap parts such as SiC FETs or GaN FETs.

In this example circuit, inductor Ll **401** is a first phase inductor, and transformer T**1** **411** is a first phase transformer. Inductor L**2** **402** is a second phase inductor, and transformer T**2** **412** is a second phase transformer. Inductor L**3** **403** is a third phase inductor, and transformer T**3** **413** is a third phase transformer. In typical designs these three phases are 120-degrees of phase from each other.

Since the inductors and transformers support large currents, each contributes to some amount of core loss from the magnetic flux within their cores. In order to minimize this core loss all three inductors and three transformers are integrated together into three-phase magnetics assembly **470**. A common inductor return leg is provided for the three inductors, and a common transformer return leg is provided for the three transformers, as illustrated in FIGS. **1**B, **1**C, and **2**B. Magnetic flux from the three phases within the single return legs acts to cancel each other out since the phases are separated by 120-degrees, thus reducing core loss within three-phase magnetics assembly **470**.

In an example embodiment, magnetic flux from each of the three inductors is sinusoidal and offset by 120-degrees, so that the combined magnetic flux from the three inductors cancels itself out to essentially zero. The magnetic flux in each transformer winding is triangular and offset by 120-degrees, so that the combined magnetic flux from the three transformer phases act to cancel each other out, and reduce the magnetic flux within the transformer return leg to ⅓ that of the flux in each individual transformer leg. This cancellation is illustrated in FIG. **7** and discussed in detail below.

FIG. **5**A illustrates the relationship **500** between inductor flux and transformer flux within an exemplary power supply circuit incorporating a three-phase magnetics assembly. In an example embodiment, such as that illustrated in FIG. **4**, magnetic flux within the inductors **510** has a sinusoidal shape, while magnetic flux within the transformers **512** has a triangular shape. The transformer magnetizing current lags from the magnetizing current within its corresponding inductor as shown here. The two currents are offset by a phase offset of φ **514**.

This relationship holds true for each of the three phases. Since each phase is offset by 120-degrees or $2\pi/3$, a phase diagram may be constructed for the fluxes within each of the inductors and each of the transformers. FIG. **5**B illustrates such a phase diagram.

FIG. **5**B is a phase diagram **520** illustrating the phase relationship between magnetic fluxes within each of the inductors and transformers within an exemplary power supply circuit incorporating a three-phase magnetics assembly. In this example, first phase inductor L**1** flux **531** is shown as a reference at 0 phase offset, each of the remaining flux components from the remaining inductors and transformers is illustrated with respect to this phase vector. First phase transformer T**1** flux **541** is offset from first phase inductor L**1** flux **531** by $\pi/2-\varphi$. Second phase inductor L**2** flux **532**, second phase transformer T**2** flux **542**, third phase inductor L**3** flux **533**, and third phase transformer T**3** flux **543** are also illustrated on phase diagram **520**.

Notice that the fluxes of first phase inductor L**1** and second phase transformer T**2** are close to being 180-degrees or π out of phase. This also holds true for second phase inductor L**2** and third phase transformer T**3**, and for third phase inductor L**3** and first phase transformer T**1**. Because of this phase relationship between the various inductors and transformers, if opposing pairs of devices were to have core legs sharing a central axis, the fluxes of the pair would essentially cancel within the portion of the core between the two devices, and greatly reduce core losses.

This pairing of the devices is illustrated in FIG. **6** and discussed in detail below. Winding arrangements such as that illustrated in FIG. **3**B are used to accomplish this pairing.

FIG. **6** illustrates a three-phase magnetics assembly **600**. In this example embodiment, unified core body **310** incorporates inductors **302**, **304**, and **306** in an inductor portion **610** of magnetics assembly **600**. Unified core body **310** also incorporates transformers **312**, **314**, and **316** in a transformer portion of magnetics assembly **600**.

Here, first phase inductor L**1** **302** is vertically aligned with and shares a core leg with second phase transformer T**2** **314**. Second phase inductor L**2** **304** is vertically aligned with and shares a core leg with third phase transformer T**3** **316**. Third phase inductor L**3** **306** is vertically aligned with and shares a core leg with first phase transformer T**1** **312**. This assembly accomplishes the pairings discussed above with respect to FIG. **5**B, and allows the magnetic fluxes of the various components to largely cancel each other out in the portion of unified core body **310** between the inductor portion **610** and the transformer portion **620**.

Note that the currents within inductors **302**, **304**, and **306** are opposite in direction to the currents within transformers **312**, **314**, and **316**, allowing the respective fluxes to cancel each other out in the portion of unified core body **310** between the inductor portion **610** and the transformer portion **620**.

FIG. **7** illustrates magnetic fluxes within each of the transformers and a common return leg within an exemplary power supply circuit incorporating a three-phase magnetics assembly. As discussed above with respect to FIG. **4**, each transformer has a magnetic flux with a triangular waveform offset from each other by 120 degrees. Here the magnetic flux within first phase transformer T**1** is shown in graph **710**, the magnetic flux within second phase transformer T**2** is shown in graph **720**, and the magnetic flux within third phase transformer T**3** is shown in graph **730**.

When these three magnetic fluxes are combined within a common return leg, the amplitude of the combined fluxes is ⅓ that of each individual transformer with a frequency three time that of the individual transformers. By combining the magnetic fluxes from the three transformers into a single transformer return leg, the amplitude of the flux is reduced by ⅔ and directly reduces core losses in the assembly.

The included descriptions and figures depict specific embodiments to teach those skilled in the art how to make and use the best mode. For the purpose of teaching inventive principles, some conventional aspects have been simplified or omitted. Those skilled in the art will appreciate variations from these embodiments that fall within the scope of the invention. Those skilled in the art will also appreciate that the features described above may be combined in various ways to form multiple embodiments. As a result, the invention is not limited to the specific embodiments described above, but only by the claims and their equivalents.

What is claimed is:

1. A three-phase magnetics assembly comprising:

a plurality of windings; and

a unified core body having a plurality of core legs which each extend in a direction of central axes of the plurality of windings and around which the plurality of windings are wound such that magnetic fluxes are produced in the plurality of core legs when current flows through the plurality of windings;

wherein the plurality of windings comprise first, second, and third phase inductors, and first, second, and third phase transformers, which are positioned about the unified core body such that the core legs of the first phase inductor and second phase transformer share a central axis, the core legs of the second phase inductor and third phase transformer share a central axis, and the core legs of the third phase inductor and first phase transformer share a central axis; and

wherein a winding direction of the first, second, and third phase inductors is opposite a winding direction of the first, second, and third phase transformers.

2. The three-phase magnetics assembly of claim **1**, wherein:

a first one of the plurality of windings comprises the first phase inductor and a primary coil of the first phase transformer;

a second one of the plurality of windings comprises the second phase inductor and a primary coil of the second phase transformer; and

a third one of the plurality of windings comprises the third phase inductor and a primary coil of the third phase transformer.

3. The three-phase magnetics assembly of claim **1**, wherein each of the core legs includes an air gap.

4. The three-phase magnetics assembly of claim **1**, further comprising:

an inductor return leg, configured to conduct magnetic flux between first and second ends of the core legs within the inductors; and

a transformer return leg, configured to conduct magnetic flux between first and second ends of the core legs within the transformers.

5. The three-phase magnetics assembly of claim **4**, wherein currents within the inductors are sinusoidal and magnetic fluxes from each of the three inductors cancel each other within the inductor return leg.

6. The three-phase magnetics assembly of claim **4**, wherein currents within the transformers are triangular and magnetic fluxes from each of the three transformers partially cancel each other within the transformer return leg.

7. A unified core body for a three-phase magnetics assembly comprising:

a plurality of core legs which each extend in a direction of central axes of first, second, and third phase inductors, and first, second, and third phase transformers, each having a first and second end, and each configured to provide a magnetic core conducting magnetic flux for one of the first, second, and third phase inductors, and the first, second, and third phase transformers;

a single inductor return leg, configured to conduct magnetic flux between the first and second ends of the core legs within the inductors; and

a single transformer return leg, configured to conduct magnetic flux between the first and second ends of the core legs within the transformersi

wherein a winding direction of the first, second, and third phase inductors is opposite a winding direction of the first, second, and third phase transformers.

8. The unified core body for a three-phase magnetics assembly of claim **7**, wherein currents within the inductors are sinusoidal and magnetic fluxes from each of the three inductors cancel each other within the inductor return leg.

9. The unified core body for a three-phase magnetics assembly of claim **7**, wherein currents within the transformers are triangular and magnetic fluxes from each of the three transformers partially cancel each other within the transformer return leg.

10. The unified core body for a three-phase magnetics assembly of claim **7**, wherein the first, second, and third phase inductors and first, second, and third phase transformers are positioned about the unified core body such that the core legs of the first phase inductor and second phase transformer share a central axis, the core legs of the second phase inductor and third phase transformer share a central axis, and the core legs of the third phase inductor and first phase transformer share a central axis.

11. The unified core body for a three-phase magnetics assembly of claim **10**, wherein:

the first phase inductor and a primary coil of the first phase transformer comprise a single winding;

the second phase inductor and a primary coil of the second phase transformer comprise a single winding; and

the third phase inductor and a primary coil of the third phase transformer comprise a single winding.

12. The unified core body for a three-phase magnetics assembly of claim **7**, wherein each of the core legs includes an air gap.

13. A three-phase magnetics assembly comprising:

a plurality of windings;

a unified core body having a plurality of core legs, each having a first and second end, which each extend in a direction of central axes of the plurality of windings and around which the plurality of windings are wound such that magnetic fluxes are produced in the plurality of core legs when current flows through the plurality of windings, wherein the plurality of windings comprise first, second, and third phase inductors, and first, second, and third phase transformers, which are positioned about the unified core body such that the core legs of the first phase inductor and second phase transformer share a central axis, the core legs of the second phase inductor and third phase transformer share a central axis, and the core legs of the third phase inductor and first phase transformer share a central axis;

an inductor return leg, configured to conduct magnetic flux between the first and second ends of the core legs within the inductors; and

a transformer return leg, configured to conduct magnetic flux between the first and second ends of the core legs within the transformers;

wherein a winding direction of the first, second, and third phase inductors is opposite a winding direction of the first, second, and third phase transformers.

14. The three-phase magnetics assembly of claim **13**, wherein:

a first one of the plurality of windings comprises the first phase inductor and a primary coil of the first phase transformer;

a second one of the plurality of windings comprises the second phase inductor and a primary coil of the second phase transformer; and

a third one of the plurality of windings comprises the third phase inductor and a primary coil of the third phase transformer.

15. The three-phase magnetics assembly of claim **13**, wherein each of the core legs includes an air gap.

16. The three-phase magnetics assembly of claim **13**, wherein currents within the inductors are sinusoidal and magnetic fluxes from each of the three inductors cancel each other within the inductor return leg.

17. The three-phase magnetics assembly of claim **13**, wherein currents within the transformers are triangular and magnetic fluxes from each of the three transformers partially cancel each other within the transformer return leg.

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